# A NUMERICAL AND AN EXPERIMENTAL INVESTIGATION OF A HIGH-PRESSURE DIE-CASTING ALUMINUM ALLOY

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## Abstract

*In this paper, a computer simulation of a high-pressure die casting of aluminum alloy was performed using a commercially available software and also compared with the real castings of the same alloy. The commercial aluminum alloy was Etial 150 (AlSi12Cu) that is used for flange which is a washing machine part. Mold filling, solidification, temperature distribution, porosity, and velocity of the liquid metal during high-pressure die casting were investigated using the model through numerical simulation. The simulation results proved that the model values used in simulations were accurate in order to apply for experimental casting. After this numerical model, the flange part was cast experimentally according to the obtained optimum parameters from simulation results. Then, specimens from the experimental casting were tested for tensile, hardness, and microstructure analyses. Accordingly, the test results are rather sound which demonstrates that simulation provides profitable die casting. Consequently, it was observed from this study that simulation is not only useful for enhancing casting quality but also very economical and practical, which helps to reduce time spent on experiments. Moreover, simulation can reveal porosity and helps to minimize this defect. Thus, computer simulation should be used for casting applications more often, and simulation programs should be developed further.*

*Keywords:* *high-pressure die casting, casting simulation software, casting simulation, casting metallurgy of aluminum alloy, etial 150, mechanical properties, etial 150 high-pressure die casting, properties of Etial 150 casting*

## Introduction

Die casting is a widely used process, which is used for manufacturing engineered metal parts. This process is carried out by forcing molten metal under high pressure into reusable steel molds. These reusable steel molds are called dies. The dies can be designed to produce complex shapes with a high degree of preciseness and repeatability. Die castings are among the highest volume, mass-produced metalworking industrial items. Die cast parts, ranging from automobiles to toys, are crucial components of products.[1]

The materials of dies, or die-casting tooling, are alloy tool steels. The dies have at least two sections, the fixed die half, or cover half, and the ejector die half, to permit removal of castings. Modern dies also may have moveable slides, cores, or other sections to produce holes, threads, and other desired shapes for castings. Sprue holes in the fixed die half allow molten metal to enter the die and fill the cavity. The ejector half usually has the runners (passageways) and gates (inlets) that route molten metal to the cavity. Dies also include locking pins to secure the two halves, ejector pins to help removing the cast part, and openings for coolant and lubricant.[1,2]

When the die-casting machine closes, the machine's hydraulic pressure locks and holds the two die halves together. The surface where the ejector and fixed halves of the die meet and lock is referred to as the "die parting line." The clamping force of the machine is governed by the total projected surface area of the part being cast, measured at the die parting line, and the pressure required of the machine to inject metal into the die cavity.[3]

Each of the metal alloys available for die casting offers specific advantages for completed parts. For instance, zinc is the easiest alloy to cast with high ductility, high impact strength and easily plated. Zinc has a low melting point and supports long die life and it is economical for small parts. Moreover, aluminum is lightweight, while having high dimensional stability for complex shapes and thin walls. Aluminum has high strength, as well as high thermal and electrical conductivity at high temperatures, good mechanical properties and corrosion resistance.[2]

The software used in this study is a comprehensive simulation tool for the technological and quality-focused production of castings worldwide. The simulation capabilities of the software show the way by providing a better understanding of mold filling, solidification, mechanical properties, thermal stresses and distortions, and much more. This software provides a complete solution for your design, production, and quality departments with fully menu-driven with an integrated solid modeler, CAD interfaces, and extensive databases as a roadmap to casting quality and optimization. Also, it helps to avoid gating and feeding problems, predict casting quality, aids permanent mold design, and reduces fettling costs.[4]

The software used for simulations of this study suggests solutions for all casting necessities with several modules. For instance, the used module in this study supplies an extensive simulation of the high-pressure die-casting (HPDC) process using particular process and boundary conditions. In this module, all important parameters affecting heat flow and the thermal balance of the die can be regarded, such as ejection time, die opening sequence, delay time (simulating effect of cycle interruptions on the thermal balance), die closing sequence, less time until the starting of the next cycle, individual control of each cooling or tempering channel, illustration of die spraying procedure, venting and vacuum, local squeezing description. This module used for HPDC also sustains the setup of shot sequence by an extensive shot calculator module, considering the casting requirements and the die-casting machine capacities. The shot calculator gives information for the simulation setup of the recommended first- and second-phase shot profile.[4,5]

The die-casting process has emerged from the original low-pressure injection method to techniques including high-pressure casting at forces over 4500 pounds per square inch-squeeze casting and semisolid die casting. These modern processes are able to manufacture high integrity, near net-shape castings with admirable surface finishes. Nowadays, in order to provide maximum profits from this process, it is crucial that designers associate with the die caster at an early stage of the product design and development with the help of simulation programs such as the one used in this study.[6]

## Simulation Steps

In this paper, HPDC of the aluminum alloy AlSi12Cu was simulated with the help of the HPDC simulation software program for the shape of the flange part, which is used for washing machine cylinders in order to make them turn. At first, the shape of the flange was drawn with the CAD program.

The quality of the CAD model of the flange was verified in Solidworks. The single flange was then cut into three separate sections: casting, gating, and ingate. These separate three models needed proper orientation on the same axis. Therefore, they were united again in an assembly.

The simulation software required all models to be imported in stereolithography, STL format. The three models in the assembly were exported as STL files created with a deviation of 0.05 and angle of 9°. The output STL files of casting, gating, and ingate were ready for import into the simulation.[7,8]

The CAD data of the flange were transferred to the simulation software. Then, material groups were selected as casting.geo, ingate.geo, and gating.geo in the preprocessor. Casting.geo, ingate.geo, and gating.geo were opened at the same time in the preprocessor stage of the simulation software. After that, biscuit, ingate, and user defined (piston), which form pressurized planes to the bottom of the gating, were defined in the preprocessor, respectively[8,9] (Figures 1 and 2).

From Figure 3, it is seen that the casting is red, the gating is gray, the air channels are yellow, the biscuit and the inlet are also gray, the piston is orange. On the right of Figure 3, message history of the preprocessor is seen.

Tracer points were defined on the top and side views of the biscuit part of the casting by clicking with the left button of mouse. The important point of clicking for the tracer points is that the tracer points should be chosen as far away from the cooling channel of the piston, and the number of the tracer points should be at least 100. Thus, tracers were saved as "tracer.geo."

In Figure 4, preprocessor outline of different views of the mold is seen. Accordingly, the casting is red, the gating is gray, the air channels are yellow, the biscuit and the inlet
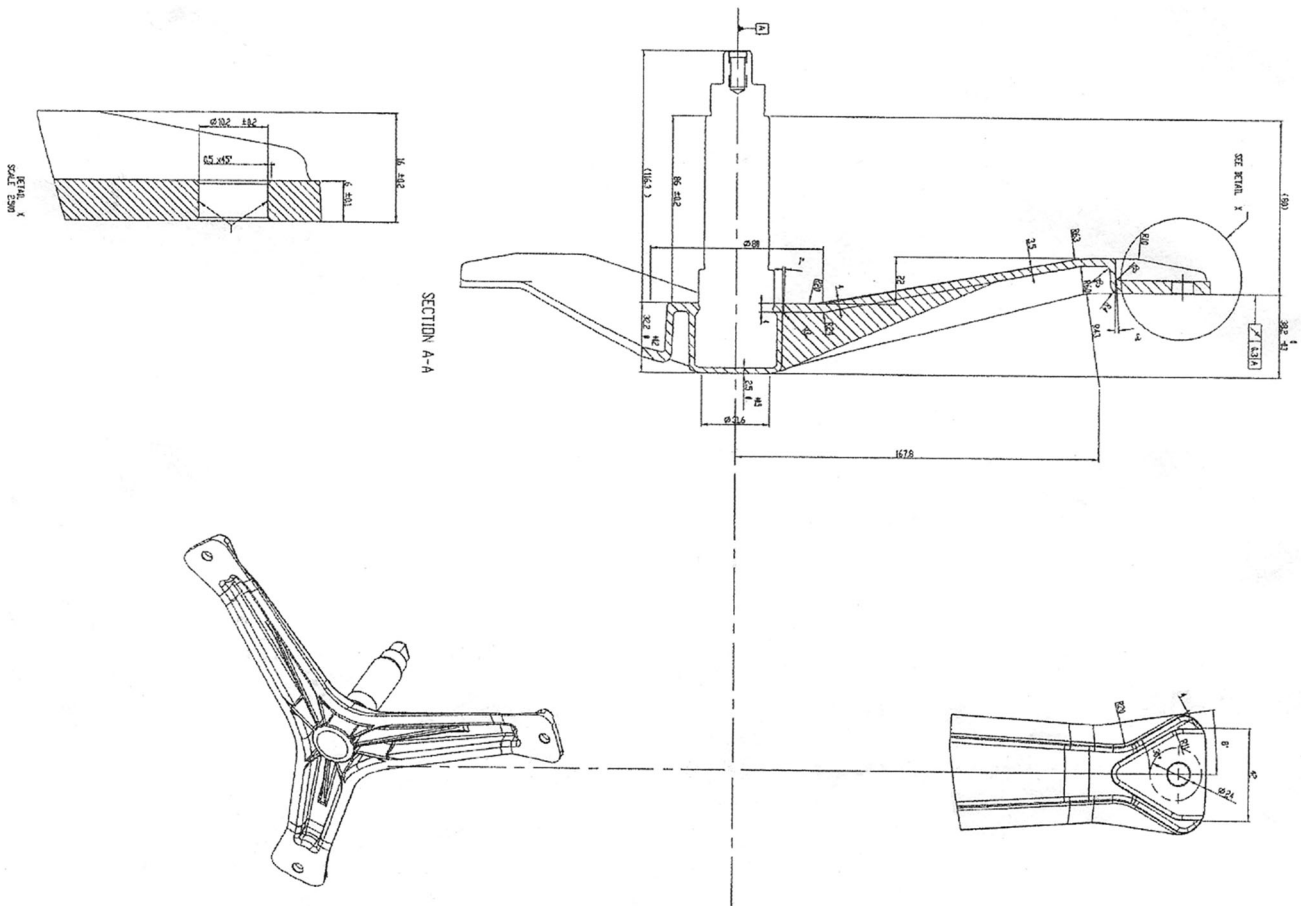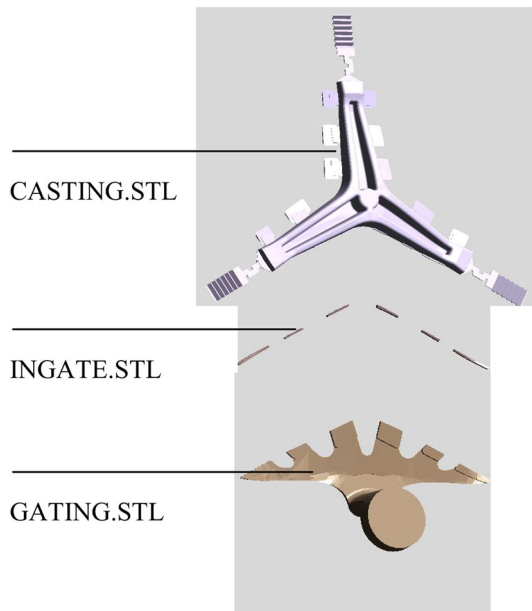
*Figure 1.  Shape of the flange which will be cast.*



CASTING.STL

INGATE.STL

GATING.STL

*Figure 2. Casting, ingate, and gating parts for the flange part saved as (\*.STL) in order to transfer simulation software.*

are also gray, the piston is orange, the cooling channels are blue, the tracer points are black in the biscuit. The cooling channel in the piston is circular, and the cooling channels in the mold are linear. The directions of axis demonstrate that the casting is in the right position as seen in Figure 4.

In order to start working on mesh elements, enmeshment values seen in the Table 1 were defined in the software.

After enmeshment had been done, simulations could be started. The material definition and heat transfer definition values were introduced to the software according to the properties of HPDC AlSi12Cu alloy. Then, volume and area data of the model were defined. After defining these geometrical data, HPDC machine data values and shot sleeve data values were introduced. After defining shot sleeve data values, HPDC process data and shot characteristics values such as velocity and ingate area were also entered to the software, respectively. Then, core open definitions and filling and solidification definitions were defined. Most of these data values are default in the
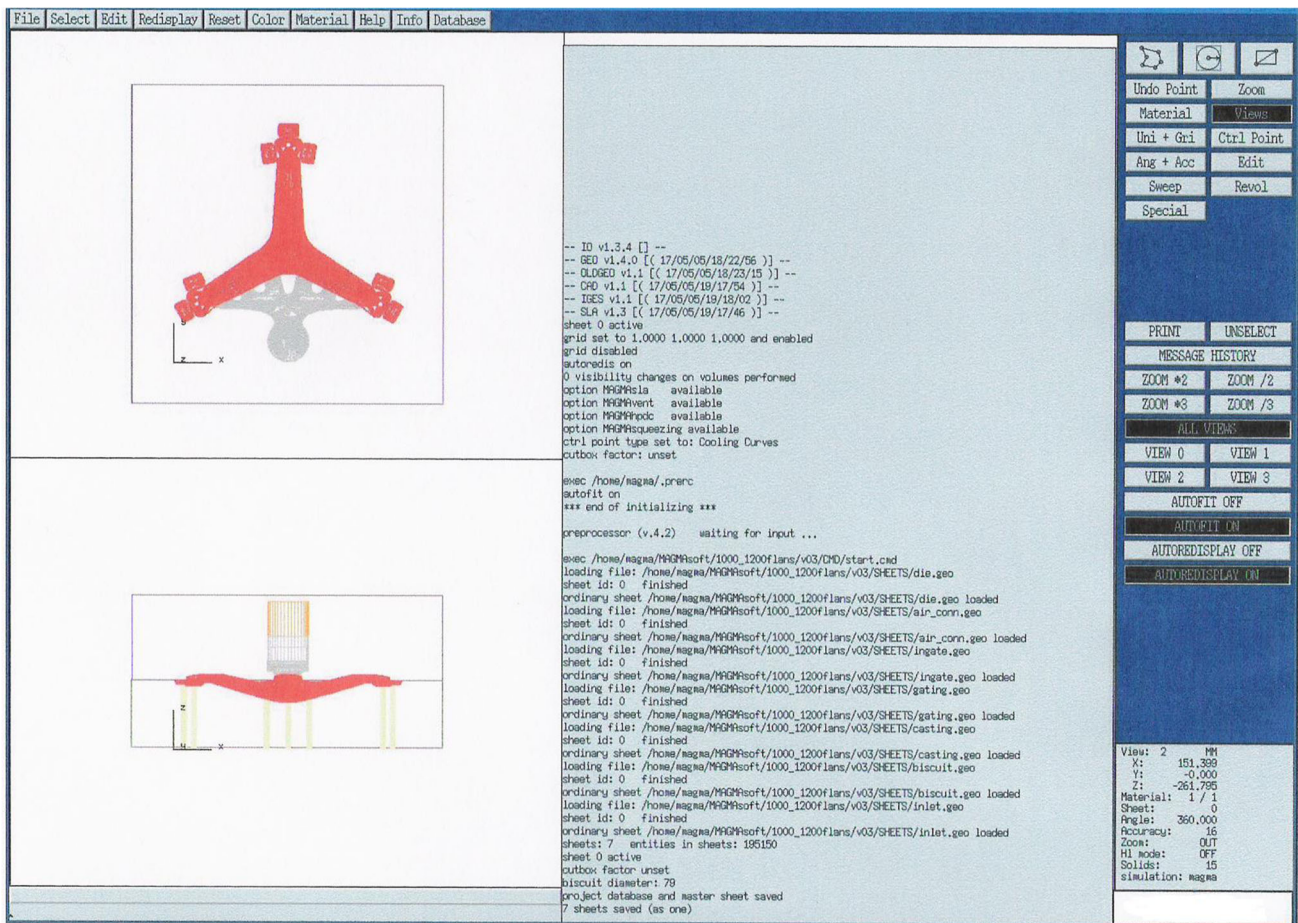
**Figure 3. Preprocessor stage outline of the biscuit, ingate, piston, and air channels on the flange (casting).**

software database according to HPDC process, Etial 150 alloy and the used machine characteristics.[4]

## Simulation Results for AlSi12Cu Flange

After all related parameters were defined, the programmer started the simulation of the HPDC alloy AlSi12Cu flange part. Five cycles of this casting process were performed throughout all simulations. Five cycled simulations are advised by the simulation programmer company in order to get optimal results since the casting reaches quasi-steady state in five cycles regardless of the casting geometry.

Five casting cycles are needed in order to perform a realistic simulation since five cycling provides heating the mold completely as observed in Figure 5 and proper mold heating is crucial for HPDC. The simulations having <5 cycles cannot heat the mold completely, and then, the simulation becomes less realistic for the casting application. For instance, if the simulation is done with one cycle instead of five cycles, an ideal simulation result cannot be obtained since the mold is not heated enough. Five cycling is only related to proper mold heating not related to the part geometry, size, shape, and thickness. Accordingly, five

cycling can obviously be observed from the five peaks of the thermocouple plot in Figure 5. All of these five peaks have approximately the same temperature values of about 220 °C which implies steady-state casting temperature just after mold closing. Moreover, the least temperature values, which are observed from Figure 5 below, are also approximately the same about 195 °C, implying not only the mold opening temperature, but also steady state of the process.

In order to take the simulation results, the related parameters were defined through the software. Process data values such as slow shot velocity, fast shot velocity, cavity filling time, velocity at the ingate are set as seen in Figure 6. These values are determined according to the previous experiments and therefore suggested as default by the software.

Initial temperature, liquidus temperature, solidus temperature of the cast alloy and its material AlSi12Cu were defined in the material definitions window through the software as observed from Figure 7. Additionally, materials and their initial temperatures, liquidus temperature, solidus temperature of the permanent mold, and cooling were also defined. As seen in Figure 7, material of the permanent mold is X40CrMoV5, and its initial temperature
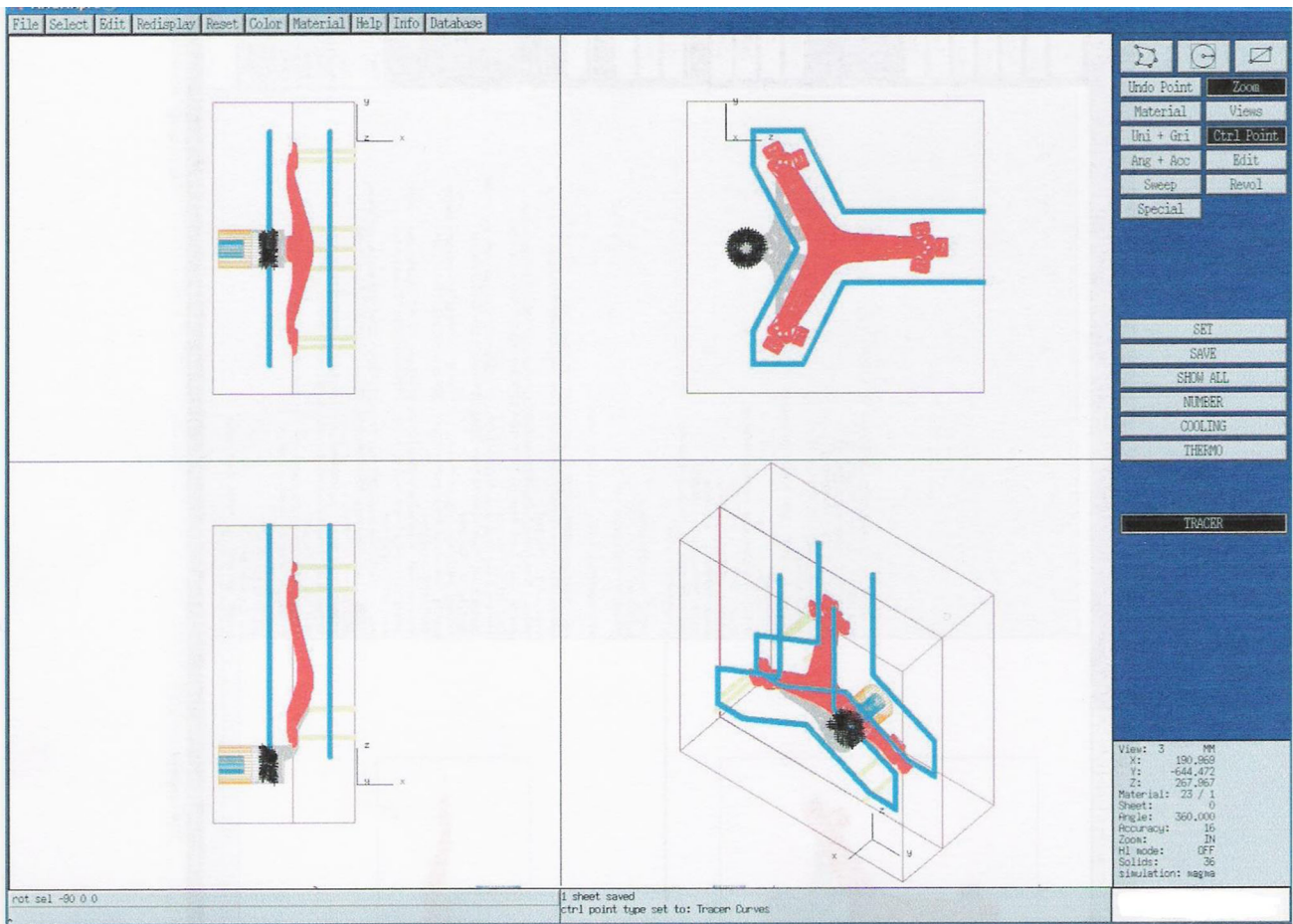
**Figure 4. Preprocessor outline of different views of the mold.**

is 200 °C. Material of the cooling is water, and its initial temperature is 20 °C.

The heat transfer definitions between the cast alloy AlSi12Cu and the permanent mold were also defined choosing the related default database through the software in the heat transfer definitions window as seen in Figure 8.

Solidification-related definitions were also defined through the default database of the software. Accordingly, the feeding calculation is requested and feeding effectivity ratio is determined as 90 % in order to stay in the safe region as observed from Figure 9. Moreover, the criterion temperatures are 488.90 and 580 °C.

## Simulation Results for the Filling Velocity

The filling velocity simulation result for 100 % of the melt that fills completely at 1690 ms is seen in Figure 13.

The velocity variation and progression can be observed from the next Figures 10, 11, 12 and 13. The general velocity, which is seen in the figures, is represented with light blue

color as comparing with the velocity scale with respect to cm/s on the right side of the figures. Moreover, the velocity increases seen in these figures are needed to accelerate the melt to reach the top of the part from the biscuit where the melt is started to be poured. Additionally, some of the velocity increases are due to the relatively thin and narrow sections of the part. For instance, there is a velocity increase from 3777 to 7553 cm/s at the center of the gating due to relatively thin volume of that side of the gating in Figure 13. The same amount of velocity increase can also be observed at the ingates due to getting narrow. Velocity increases are also visible at the upper side of the casting, because the last zone to be filled is the upside of the flange. Since the liquid metal was at a higher pressure, it travelled a longer distance while going upward in the flange.[9,10]

Consequently, a rather uniform and accurate velocity distribution is observed at the simulation result shown in Figure 13 during filling. This uniform velocity is nearly typical high-pressure die-casting velocity. The filling velocity simulation result demonstrates mold filling and turbulence ideally. Since turbulence is not observed from these simulation result figures of velocity, it can be stated that there is no turbulence in terms of the filling velocity.

**Table 1. Values that were Entered to Enmeshment Stage of the Software in Order to Provide the Most Accurate Meshes**

| | Mesh standard | Mesh advanced | Mesh advanced 2 |
|---|---|---|---|
| Accuracy | | | |
| x | 3 | 3 | 3 |
| y | 3 | 3 | 3 |
| z | 3 | 3 | 3 |
| Wall thickness | | | |
| x | 10.00 | 2.90 | 0.90 |
| y | 10.00 | 2.90 | 0.90 |
| z | 10.00 | 2.90 | 0.90 |
| Element size | | | |
| x | 10.00 | 2.00 | 0.60 |
| y | 10.00 | 2.00 | 0.60 |
| z | 10.00 | 2.00 | 0.80 |
| Smoothing | 3.00 | 2.00 | 2.00 |
| Ratio | 5.00 | 3.00 | 3.00 |
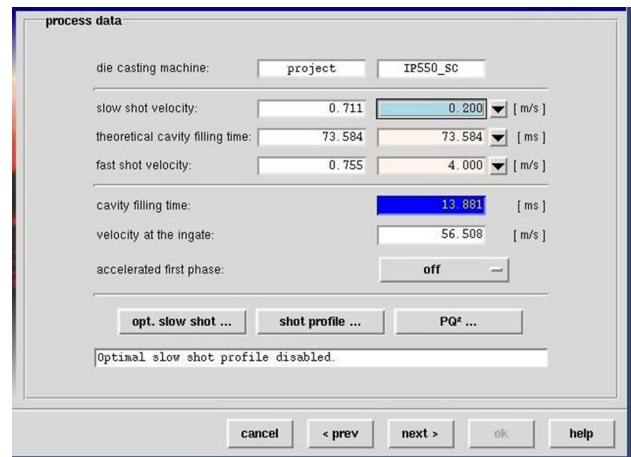


*Figure 6.  Process data values.*

## Simulation Results for the Filling Temperature

The filling temperature simulation results for 100 % filling at 1690 ms is seen in Figure 14.
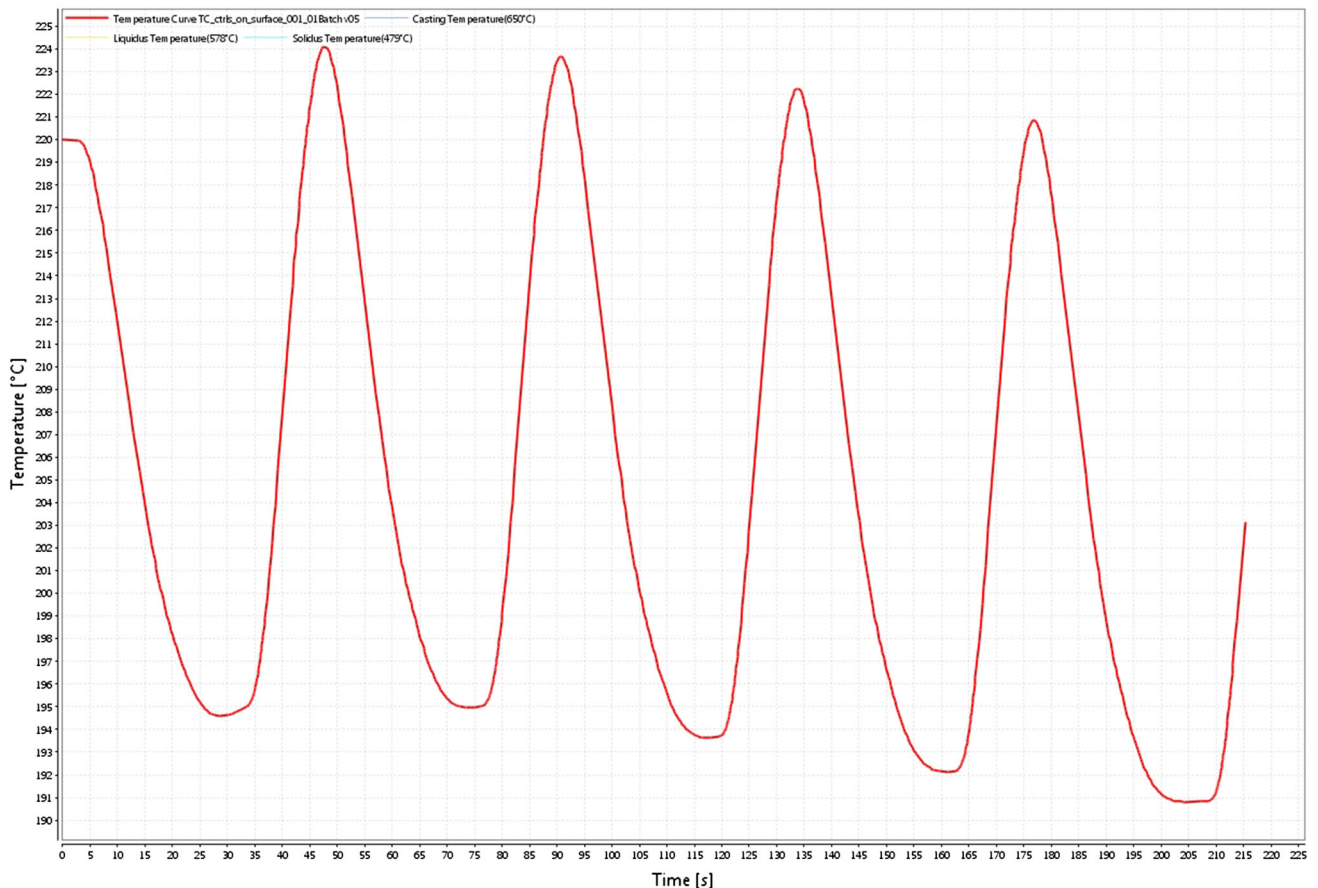


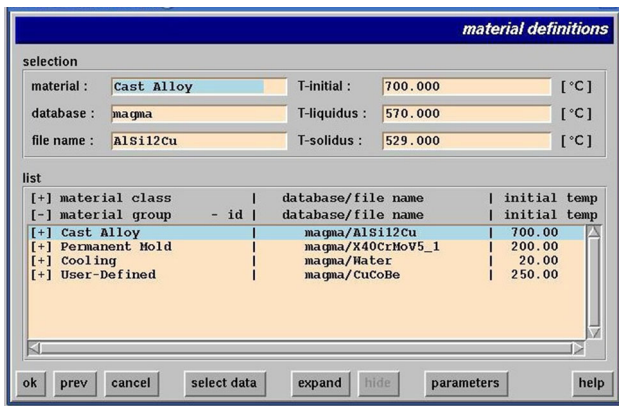**Figure 5.  Temperature versus time curve of five cycling.**

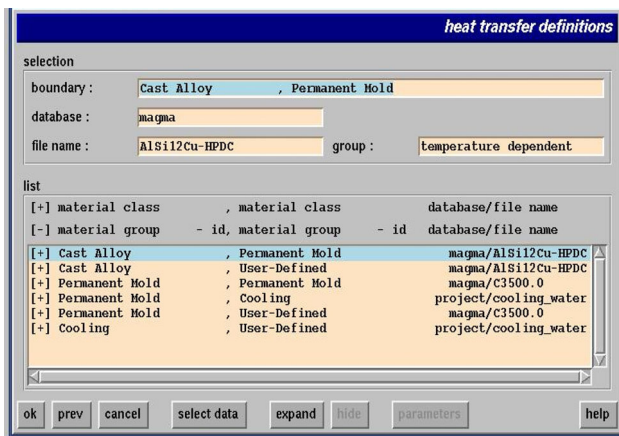**Figure 7. Values of material definitions.**



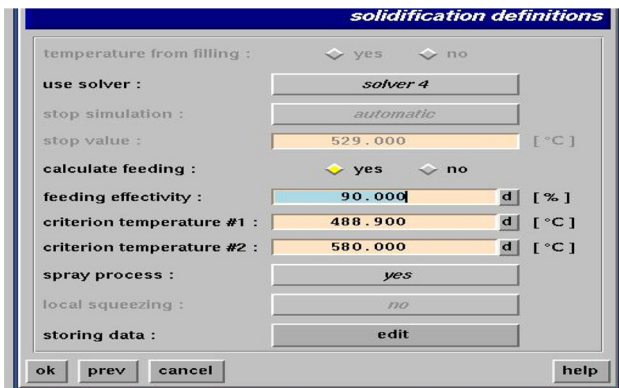**Figure 8. Heat transfer definitions window.**



**Figure 9. Solidification definitions window.**

The general filling temperature throughout the casting is 635.5 °C represented by yellow color as observed in Figure 14. Moreover, the general temperature of the liquid metal throughout the gating, upper two ingates, and exits of the upper two ingates was 640 °C represented by very light yellow. However, 631.1 °C temperature demonstrated by dark yellow color can also be seen in some regions of the casting such as edges, overflows, and upside due to the geometry.
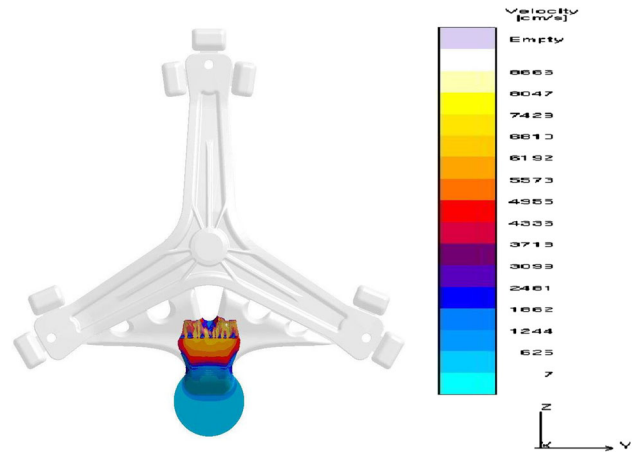


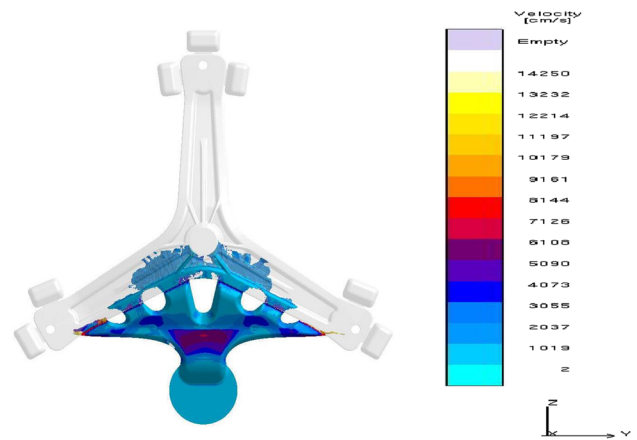**Figure 10. Representation of filling velocity simulation result for 54.14 % of filling.**



**Figure 11. Representation of filling velocity simulation result for 78.02 % of filling.**
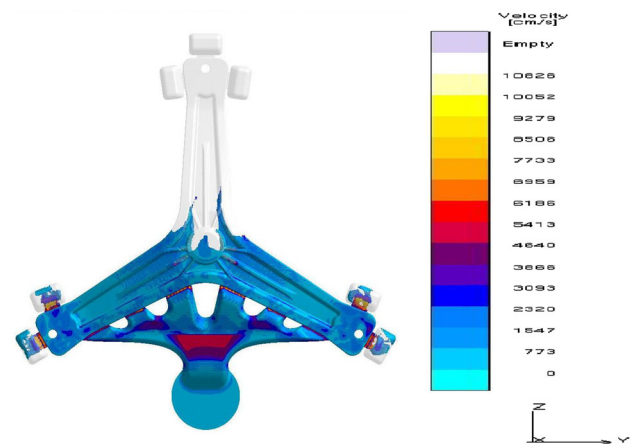


**Figure 12. Representation of filling velocity simulation result for 90.02 % of filling.**

In the biscuit region, there is stepped temperature increase from the bottom edge of the biscuit which is 595.4 °C, (blue color) to the top edge of the biscuit which is 640 °C, (yellow color), because there is a piston, which pushes the
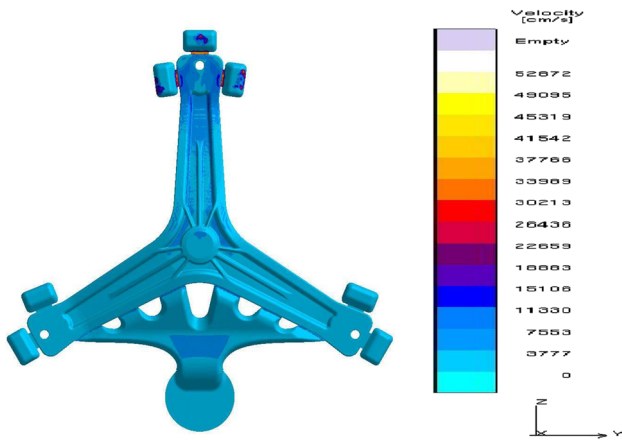
**Figure 13. Representation of filling velocity simulation result for 100 % of filling.**
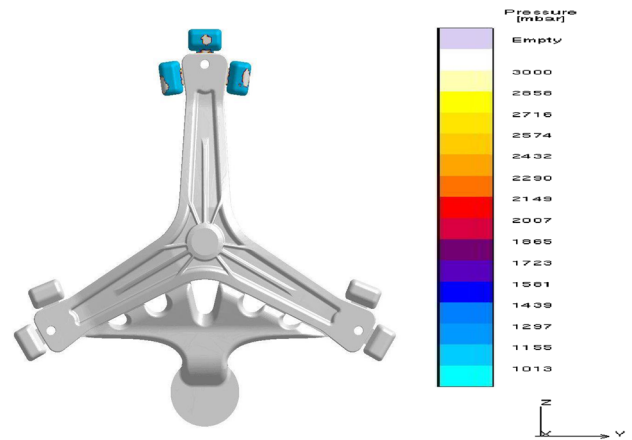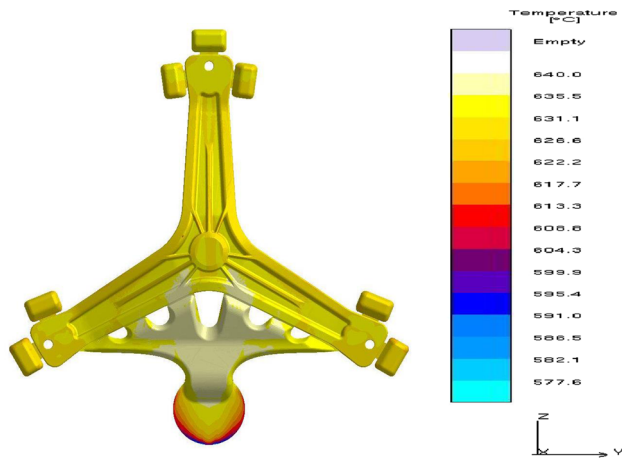


**Figure 14. Filling temperature simulation result for 100 % of filling.**

liquid metal into the mold, just behind the biscuit. This piston works with grease since the piston is cooled against corrosion. In order to impede thermal expansion, the piston is also cooled with water. Therefore, the biscuit becomes cool due to these effects. Thus, there is approximately 50 °C temperature difference in the biscuit. However, the important feature is that related to the casting, not the biscuit since the biscuit, gating, and ingate will be removed after casting. Thus, the temperature changes in the biscuit, gating, and ingate do not interfere.[10,11]

Eventually, a homogeneous temperature distribution is observed from the temperature simulation result in Figure 14 since there is not different color than yellow tones in the casting part. Thus, this homogeneous temperature distribution demonstrates that the solidification will be without issues.

## Simulation Results for the Filling Pressure

The filling pressure simulation result for 100 % of filling at 1690 ms can be seen in Figure 15.



**Figure 15. Filling pressure simulation of 100 % filling completed.**

All parts of the gating, ingate, and casting are light gray color as observed from Figure 15. Thus, the unique pressure in the gating, ingate, and casting is 3000 mbar as comparing with the scale on the right side of Figure 15. The only different color, which is light blue, is observed in the upper overflows. The overflows are air vents, and they are not as crucial as the casting part since they will be cut after solidification. Thus, pressure change from 3000 to 1155 mbar in the overflows is not so critical. Consequently, the pressure distribution for 100 % filling is very homogenous and accurate. So, melt filling pressurization is smooth, which is consistent with problem-free solidification.[12]

## Simulation Results for the Air Entrapment

The filling air entrapment simulation result for 100 % of filling at 1690 ms is observed in Figure 16.

It is observed from Figure 16 for 100 % filling that the filling air entrapment of the gating colored with turquoise is generally 0 %. However, there is 7.2 % air entrapment in the small right region of the biscuit and in the two bottom
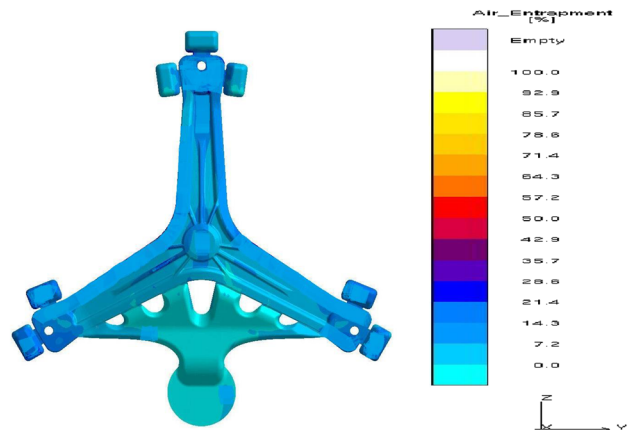


**Figure 16. Filling air entrapment simulation result for 100 % of filling.**

runners colored with light blue. The general air entrapment in the casting is 7.2 %. The blue-colored regions representing 14.3 % air entrapment are also not so important for accurate casting since some of them are thin sections and some of them are in the overflows. Consequently, the blue tones are dominating color on the casting, which demonstrate a homogenous and problem-free air entrapment distribution. Since there is no light yellow color representing 100 % air entrapment in Figure 16, it can be said that there is not crucial air entrapment event through the casting operation.[13,14]

## Simulation Results for the Solidification

In Figure 17, the solidification time simulation result of 100 % of filling for five cycles is seen.

It is observed from Figure 17 that the solidification for five cycles is completed at 7.002 s entirely. Therefore, it can be said that this solidification process of high-pressure die casting for the alloy AlSi12Cu is rather reasonable.

The regions, which solidify last at 7.002 s, are the center of overflows, the corners of the casting, the vicinity of the navel, and the gating shown with light yellow. Besides, the regions which solidify earlier are the outer edges of the casting, outer edges of the overflows, the edges navel, and the thin sections connected to the navel colored with blue corresponding to 2.982 s approximately. It is generally seen that thick sections in the mold solidify slower and later, yet thin sections solidify faster and earlier since heat transfer is faster in the thin sections.

The solidification time of the other regions can be understood by comparing their colors with the solidification timescale in Figure 17. The solidification time for the gating is getting shorter from the runners to the ingates step by step from 7.002 to 4.078 s since solidification time is approximately 7.002 s in the biscuit and approximately 4.078 s in the ingates.
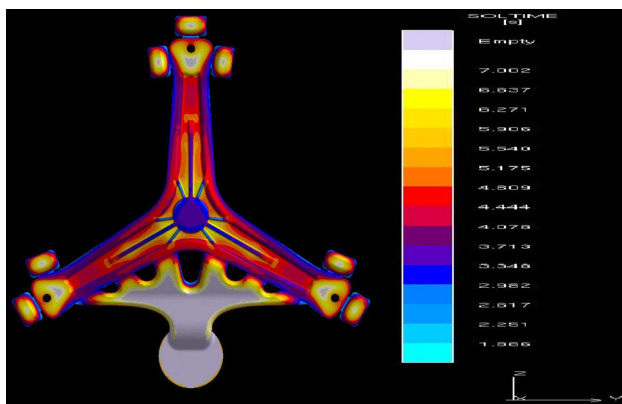
The solidification temperature simulation result when 96.52 % of casting operation was completed at 17 s for five cycles is observed from Figure 18. The turquoise color seen throughout the casting corresponds to the lowest solidification temperature 529 °C. Apart from the temperature 529 °C, there is also 537.8 °C temperature at very small points in the three corners of the casting and the center of the overflows shown with blue. As the solidification progresses, temperature decreases and these blue points turn to turquoise. The temperature at the center of the runner is 546.6 °C represented with dark purple. However, 546.6 °C temperature changes to 529 °C gradually through the ingates since the temperature in the ingates is also 529 °C. Thus, the casting, which is the real significant part, has generally turquoise color representing the lowest temperature according to the temperature scale on the right side of Figure 18. Accordingly, the solidification progress can be observed with the help of the solidification time and solidification temperature simulation results in Figures 17 and 18.[15,16]

## Simulation Results for the Feeding

Feeding is very crucial for a sound casting since many voids might occur at the casting part if feeding is not done properly. Additionally, these voids can be determined with the help of X-ray and metallographic inspections. The software used can calculate the feeding and possible cooling shrinkage voids after completely feeding of the mold filling with the analytical approximations with respect to temperature, thickness of the part, viscosity of the melt, properties of the mold especially about heat transfer.

The feeding simulation result for five cycles is observed in Figure 19. It is seen from this figure that all the colored points are light yellow which demonstrate 99.99 % feeding, according to the feeding percentage scale that differs between light blue 80 % and light yellow 99.99 % on the right side of Figure 19.
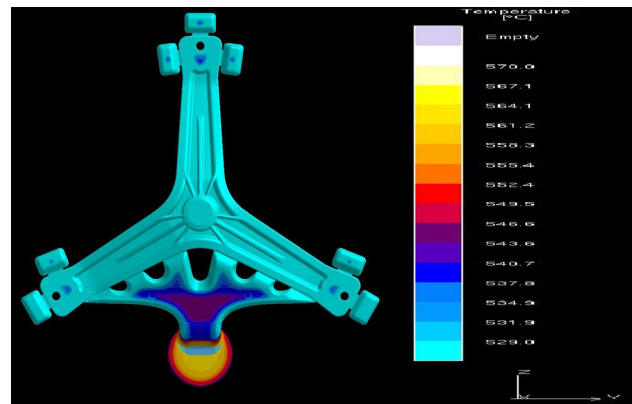


**Figure 17.** *Solidification time simulation result of 100 % filling completed.*



**Figure 18.** *Solidification temperature simulation result when 96.52 % of casting operation was completed.*
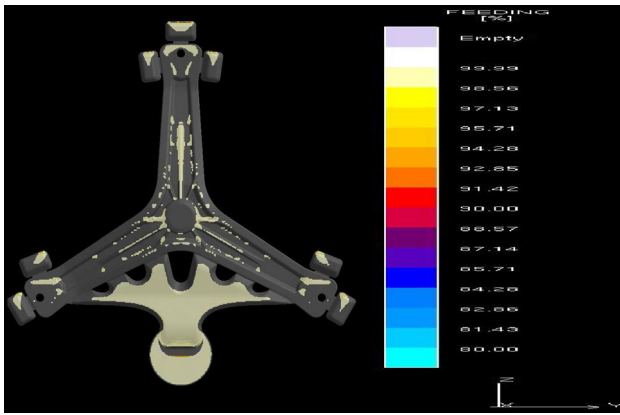
*Figure 19. Feeding simulation result.*

There is only 98.56 % feeding in the small yellow zones of the overflows and the biscuit, but this is not significant because these overflows, biscuit, and gating, ingate are cut and thrown away after casting was finished completely. Thus, the feeding of the casting is very sound, and in other words, the soundness of the casting is reasonable.[17,18]

## Simulation Results for the Hot Spots

Hot spots indicate regions that solidified later with excessive heat issues. Excessive warming might be due to the segregation in the casting part after solidification. Hot spots might cause shrinkage voids. Hot spots are mainly related to feeding since the zones, which cannot be fed properly, solidify last. Additionally, hot spots are generally seen in the thick sections.

The yellow-toned hot spots are around the biscuit, around the gating, at the center of the three corners of the casting and at the center of the overflows as observed from Figure 20. In these regions, the light yellow tone represents hot spot for 7.002 s, the yellow tone represents hot spot for 6.756 s, and the dark yellow tone represents hot spot for
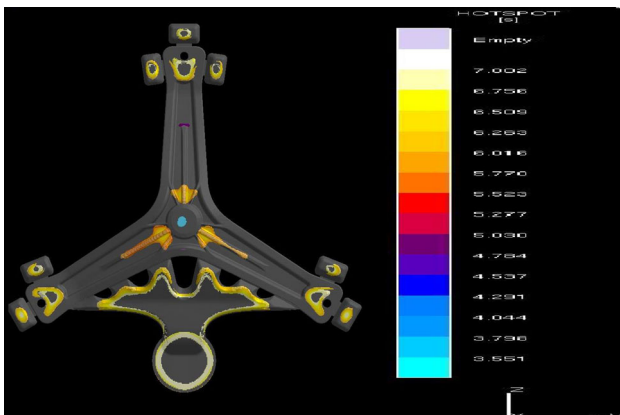
6.509 s according to the scale on the right side of Figure 20. Additionally, there is more light yellow hot spot in the biscuit. However, this is not risky as it is still under critical level, and casting part is more crucial than the biscuit and the gating parts.

There is a small light blue hot spot representing 3.798 s at the center of the casting. There are three orange hot spots representing 6.016 s in the three sides of the navel of the casting. There are also a small dark purple hot spot representing 5.030 s, and a very small purple hot spot representing 4.784 s in the casting. However, these hot spots are not dangerous because their time periods are not so long. Thus, they do not affect problemless solidification. Furthermore, it is seen from the hot spot simulation result that the hot spots are in the same points as the feeding simulation result as the hot spots occur upon feeding.[19]

## Simulation Results for the Porosity

Porosity is related to shrinkage voids due to feeding. Porosity is an undesirable casting parameter which can be calculated mathematically. Thus, the used simulation program software is able to calculate the porosity theoretically with respect to the parameters such as casting temperature, solidification range, alloy properties, and shape of casting part. Thus, the porosity simulation result of the software gives information about the possible porosity which might occur.[20]

In Figure 21, the solidification porosity simulation result for five cycles is observed. According to this simulation picture, the possible porosity percentage which might occur in the light purple-colored corners of the casting and in the thin sections of the casting is 1 % since light purple color represents 1 % porosity according to the porosity scale with respect to percentage on the right side of Figure 21. The porosity level is low enough accordingly because it is reasonable to expect 1 % porosity in these regions.
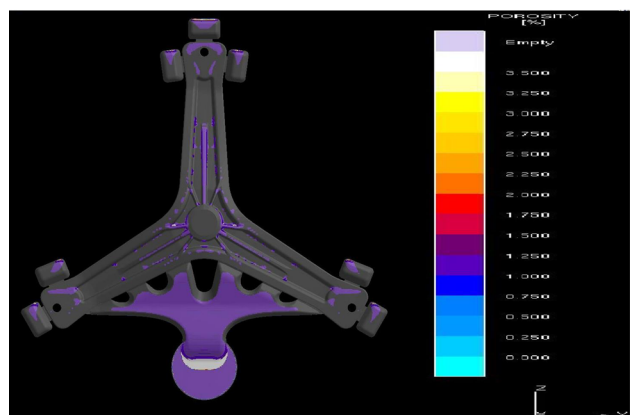


*Figure 20. Simulation result of solidification hot spots.*



*Figure 21. Solidification porosity simulation result.*

## Table 2. High-Pressure Die-Casting Machine Adjusting Parameters

| | |
|---|---|
| First-phase velocity | 0.2 m/s |
| Second-phase velocity | 3.8 m/s |
| Third-phase pressure | 280 bar |
| Point of passing to the third phase | 320 mm |
| Vice time | 8 s |
| Pump pressure | 150 bar |
| Temperature of the liquid metal | 680–695 °C |
| Mold temperature | 200 °C |

## Experimental Work

The AlSi12Cu alloy was melted at 700 °C (1292 °F) in the main melting furnace. Then, this AlSi12Cu melt was sent to the resting furnace near the high-pressure die-casting machine IP550.

After the mold, which was connected to the HPDC machine at the temperature interval between 200 and 240 °C, was sprayed with the separating grease, the vice of the HPDC machine IP550 was closed. The ladle, remained in the liquid metal at the resting furnace, then was transferred to the HPDC machine at the parameters in Table 2. The HPDC machine made the injection pin move, and the liquid metal was pressed by the piston in front of the pin in the mold.

When solidification time was completed, the vice was opened at the adjusted time. After pushing, the flange was taken by operator. After waiting for approximately 5 min to cool the flange, it was trimmed in order to remove the gating, ingate, the risers (overflows), and air pockets. After checking the flange visually, it was put into the container of the sound parts.

On account of estimating solidification behavior of the casting alloy, Chvorinov equation is utilized with respect to the casting values as seen in Table 2. This Chvorinov equation is:

$$t = B\left(\frac{V}{A}\right)^2$$
$$B = \left(\frac{\rho\sqrt{\pi\alpha}[L_M + C_M(T_D - T_1)]}{2K(T_1 - T_o)}\right)^2$$

## Tensile Testing of the Casted AlSi12Cu Flange

The flange, which is a washing machine part, was cast in the HPDC machine according to the simulation data. In order to analyze the tensile strength of the casted flange, tensile testing was applied to the specimens, which were taken from the casting part of the flange.
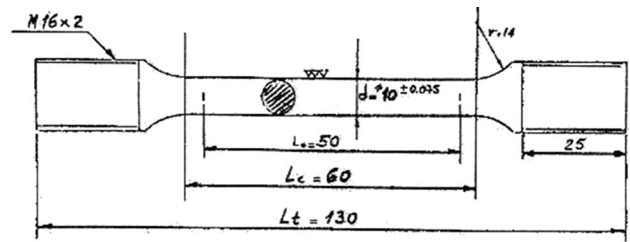


Figure 22. Dimensions of the tensile test specimen.

Tensile testing specimens were machined to a standard size for tensile testing according to TS 138 as seen in Figure 22. The HPDC specimens were fractured in a tensile testing machine (Figure 23).

The load–extension data in Figure 24 were recorded to evaluate the tensile properties. The tensile testing results data demonstrate very good agreement with data in the literature.



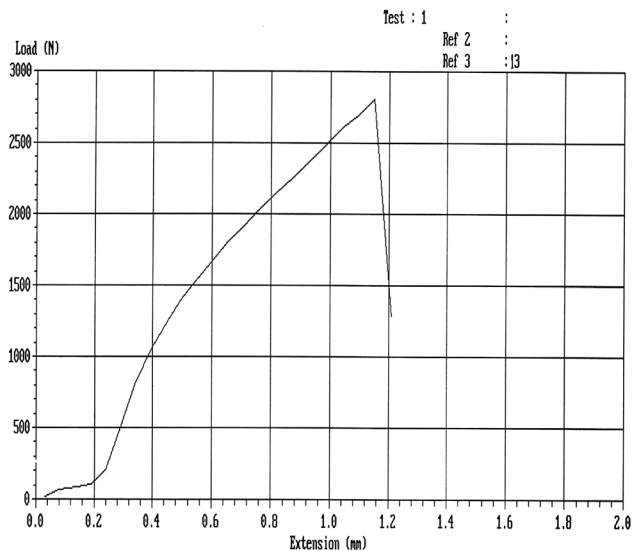Figure 23. Three high-pressure die-cast tensile test specimens ready for testing.



Figure 24. Load–extension diagram of the high-pressure die-casted specimen.

**Table 3. Mechanical Test Results Obtained from the High-Pressure Die Cast Etial 150 Flange**

| Sample no. | $D_0/2$ (mm) | $L_0$ (mm) | Load ($N$) | $\varepsilon_f$ (%) | $\sigma_{TS}$ (N/mm$^2$) | HB |
|---|---|---|---|---|---|---|
| 1 | 6 | 30 | 4052 | 2.3 | 143.3 | 89.7 |
| 2 | 6 | 30 | 2773 | 1 | 98.1 | 89.7 |
| 3 | 6 | 30 | 2804.8 | – | 99.2 | 87.75 |

As observed in Table 3, tensile strength of the first sample $\sigma_{TS1}$ is 143.3 N/mm$^2$, tensile strength of the second sample $\sigma_{TS2}$ is 98.1 N/mm$^2$, and tensile strength of the third sample $\sigma_{TS3}$ is 99.2 N/mm$^2$. Thus, the average tensile strength value of these three values is 113.53 N/mm$^2$. Additionally, Brinell hardness of the first sample HB$_1$ is 89.7, Brinell hardness of the second sample HB$_2$ is 89.7, and Brinell hardness of the third sample HB$_3$ is 87.75. Thus, the average Brinell hardness value of these three values is 89.05.

## Microstructure of the Casted AlSi12Cu Flange

The microstructure of the second specimen can be observed from Figure 25. The magnification ratio of the micrograph is ×500, and the specimen is etched for a clearer image resolution.

Figure 25 demonstrates that both silicon flakes and also faceted primaries are refined. Moreover, porosity is eliminated which is consistent with porosity simulation result.

The microstructure of the third specimen can also be observed from Figure 26. The magnification ratio of the micrograph is ×500, and the specimen is etched. It is demonstrated from Figure 26 that faceted silicon primaries are still present. However, they are refined due to high pressure. Furthermore, no porosity is present in the aluminum rich matrix.
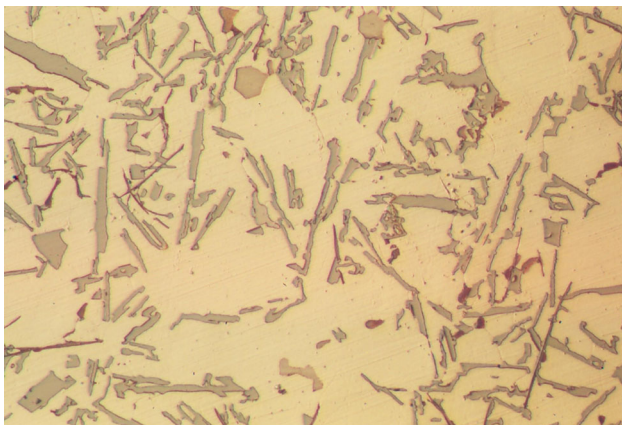


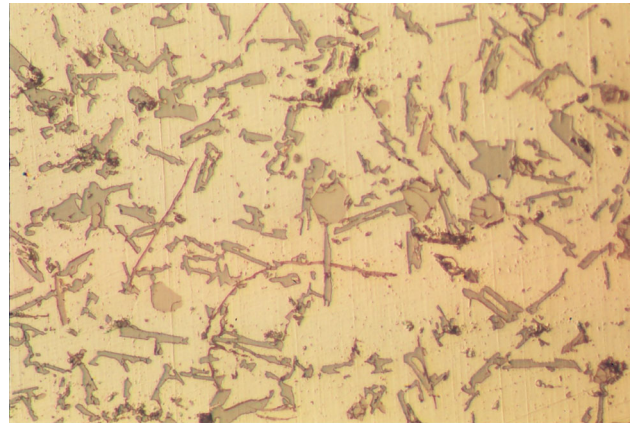**Figure 25. Microstructure of the second high-pressure die cast (etched) sample, ×500.**



**Figure 26. Microstructure of the third high-pressure die cast (etched) sample, ×500.**

## Conclusion and Outlook

- Simulation results are in good agreement for experimental application.
- Simulation is the best way to develop casting quality. It is also very economical and practical, since one can change every parameter (die temperature, casting temperature, pressure, mold design, etc.) in the computer simulation very easily and then go on to try the results in real casting. This helps to reduce time spent on experiments.
- For optimum and reliable results, minimum five cycles are needed to be carried out through the simulation software. The simulation results done with five cycles give the most realistic values according to the experiences from the other simulations done up to the present. Because the mold is heated sufficiently by five cycling as the real casting application, the real-like optimum values are obtained. Therefore, the simulations are in general recommended to be done with at least five cycling according to the prior experiences of the simulation program for all high-pressure die-casting parts not concerning the sizes and shapes of the parts.
- One of the most crucial parameters in casting quality is the porosity, because the main reason for product rejection is due to porosity (either gas or shrinkage). Since simulation can reveal porosity

and helps to minimize this defect, the use of computer simulations in casting process increases the casting quality significantly.

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## Technical Review and Discussion

## A Numerical and an Experimental Investigation of a High-Pressure Die Casting Aluminium Alloy

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**Reviewer:** Why steady state is always achieved in 5 cycles regardless of the geometry? What if the casting is thicker or thinner?

*Authors: Five cycles of casting are needed in order to perform a realistic simulation since five cycling provides heating the mould completely. And proper mould heating is crucial for high-pressure die casting. The simulations having less than five cycles cannot heat the mould completely, and then, the simulation becomes less realistic for the casting application. For instance, if the simulation is done with one cycle instead of five cycles, an ideal simulation result cannot be obtained since the mould is not heated enough. Five cycling is only related to proper mould heating and not related to the part geometry, size, shape and thickness.*

**Reviewer:** The authors state that since the temperature is uniform, the solidification would be uniform. This seems to be challenged later in the paper (in Sect. 3.3 and again in 3.6). Please clarify.

*Authors: The temperature results in Sect. 3.2 are consistent with the results in Sects. 3.3 and 3.6. The unfavourable parts observed in Sects. 3.3 and 3.6 are both negligible, and they are not in the major casting part. There are hot spots in Sect. 3.6. However, the levels of these hot spots are not dangerous and they are not permanent. Therefore, it can be accepted as uniform. Accordingly, a homogeneous pressure distribution is observed from Sect. 3.3 and there is only pressure change in the overflows, but this is not crucial since this area of overflows will be cut off after the solidification.*

**Reviewer:** The conclusion states that a minimum of 5 cycles are needed. Is that for a part of this size and shape? Is this all castings in general? Can you provide validation?

*Authors: The simulation results done with 5 cycles give the most realistic values according to the experiences from the other simulations done up to the present, because the mould is heated sufficiently by five cycling as the real casting application, and thus, the real-like optimum values are obtained. Therefore, the simulations are in general recommended to be done with at least five cycling according to the prior experiences of the simulation programme for all high-pressure die casting parts not concerning the sizes and shapes of the parts.*

**Reviewer:** The simulation results still show significant porosity in the biscuit area. This does not match the tensile specimen data that were presented.

*Authors: There is porosity in biscuit, but there is negligible porosity in the major casting part. Besides, biscuit will be cut and discarded after solidification and the major casting part will be utilized. Therefore, the porosity seen in the biscuit part does not affect the casting quality. Thus, the testing data are compatible with the simulation data.*